Paper Presentation

Rapid, artifact-reduced, image reconstruction for super-resolution structured illumination microscopy

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Outline

A. Overview

B. Background - Structured Illumination Microscopy

- From Wiener SIM to HiFi SIM (RL Algorithm)
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D. Results & Analysis

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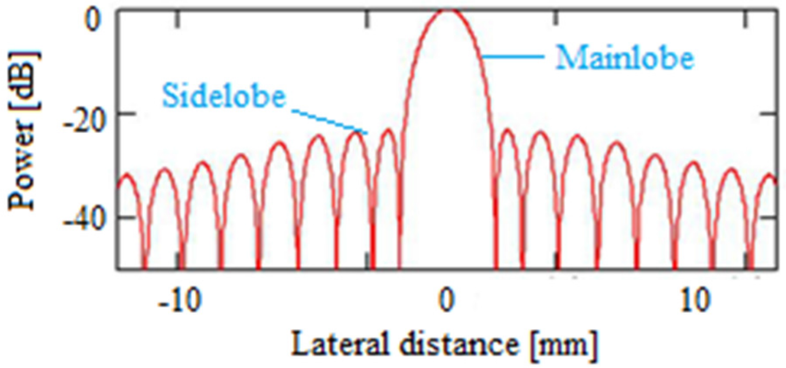
Overview

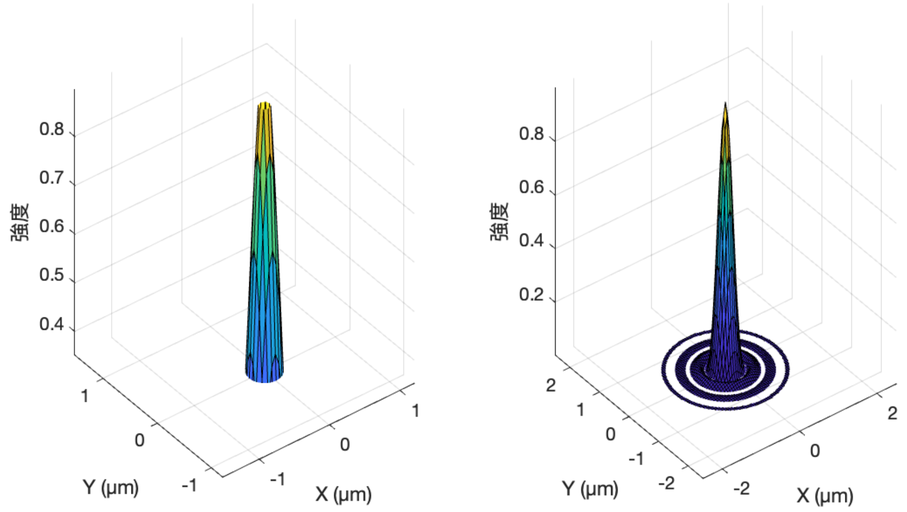
Rapid, artifact-reduced, image reconstruction for super-resolution structured illumination microscopy
Wang Z, Zhao T, Cai Y, et al.

Published April 13, 2023

- Combining high-speed reconstruction framework with high fidelity optimization approach designed to suppress the sidelobe artifact.



Reference: https://www.mdpi.com/2076-3417/6/11/359



- Achieve a real-time (millisecond-level, not include parameters estimation) reconstruction, display, and storage of high-fidelity, super-resolved images of the samples is achieved

Demo of the proposed method

The real-time reconstruction and display results of Argo-SIM slide.

Argo-SIM Slides

Reference: https://www.sciencedirect.com/science/article/pii/S266667582300053X

Reference: https://www.klv.co.jp/product/slide-microscope/argo-hm-v2.html

Structured Illumination Microscopy

Merits:

- A kind of Far-field super-resolution fluorescence microscopy

  => Larger Field of View, simpler operation

  => good for to visualize the fine details of intracellular structures.

- Enables high-speed imaging while minimizing photodamage

  1. Lower Illumination Intensity
  2. Wide-Field Illumination

Current Drawbacks:

- Reconstruction Artifacts
- SIM image acquisition and reconstruction process are separated (online v.s. offline) and time-consuming

Wiener SIM

Parameters Estimation

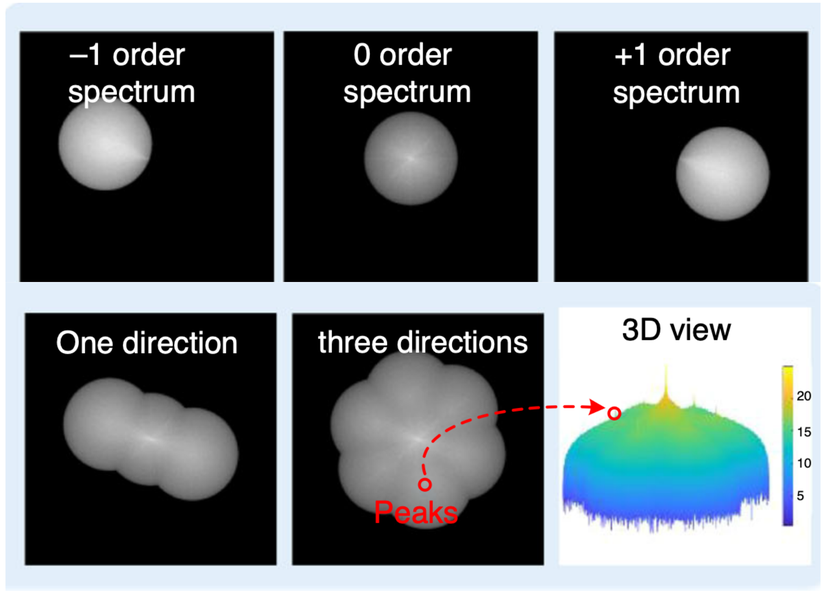
Input Images * 9
(3 Frequency bands)

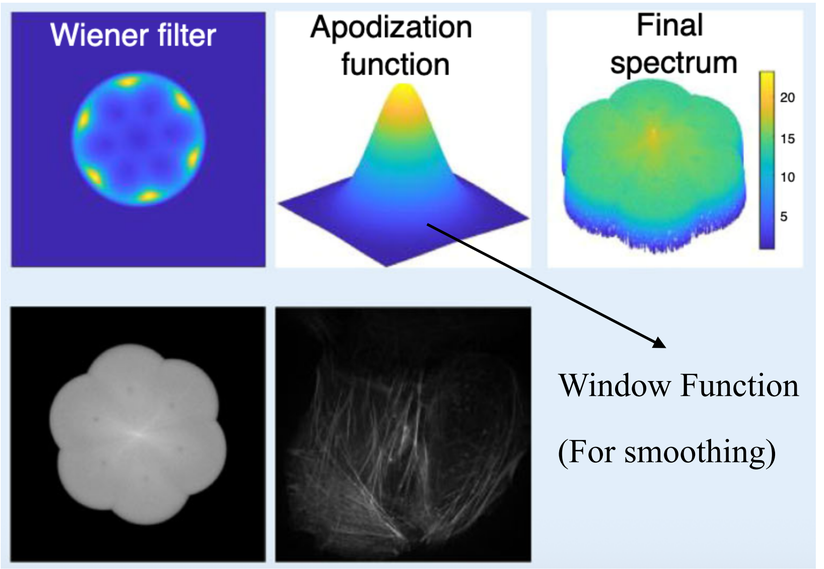
→

Spectrum Separation,
Translation, & Summation

→

Filtered and
Inverse Fourier Transform

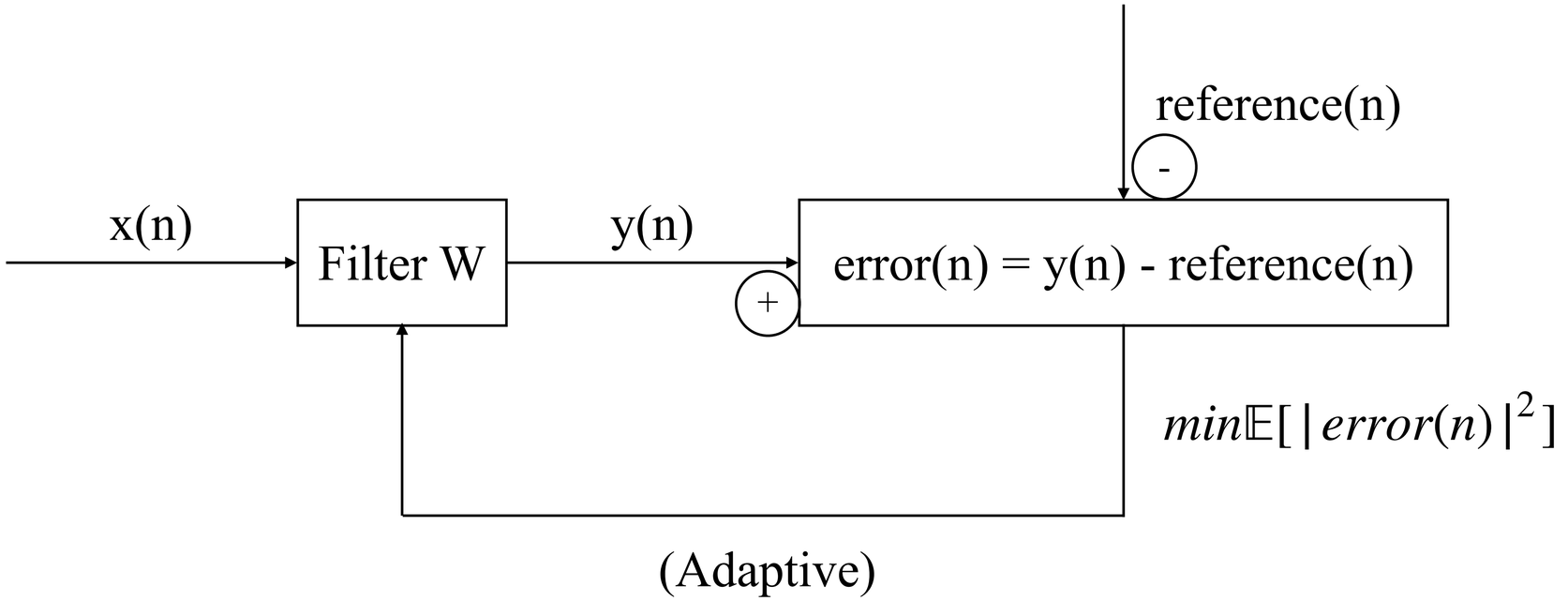




Suppress noise!
Increase resolution!

Reference: https://www.nature.com/articles/s41377-023-01204-4

Wiener Filter

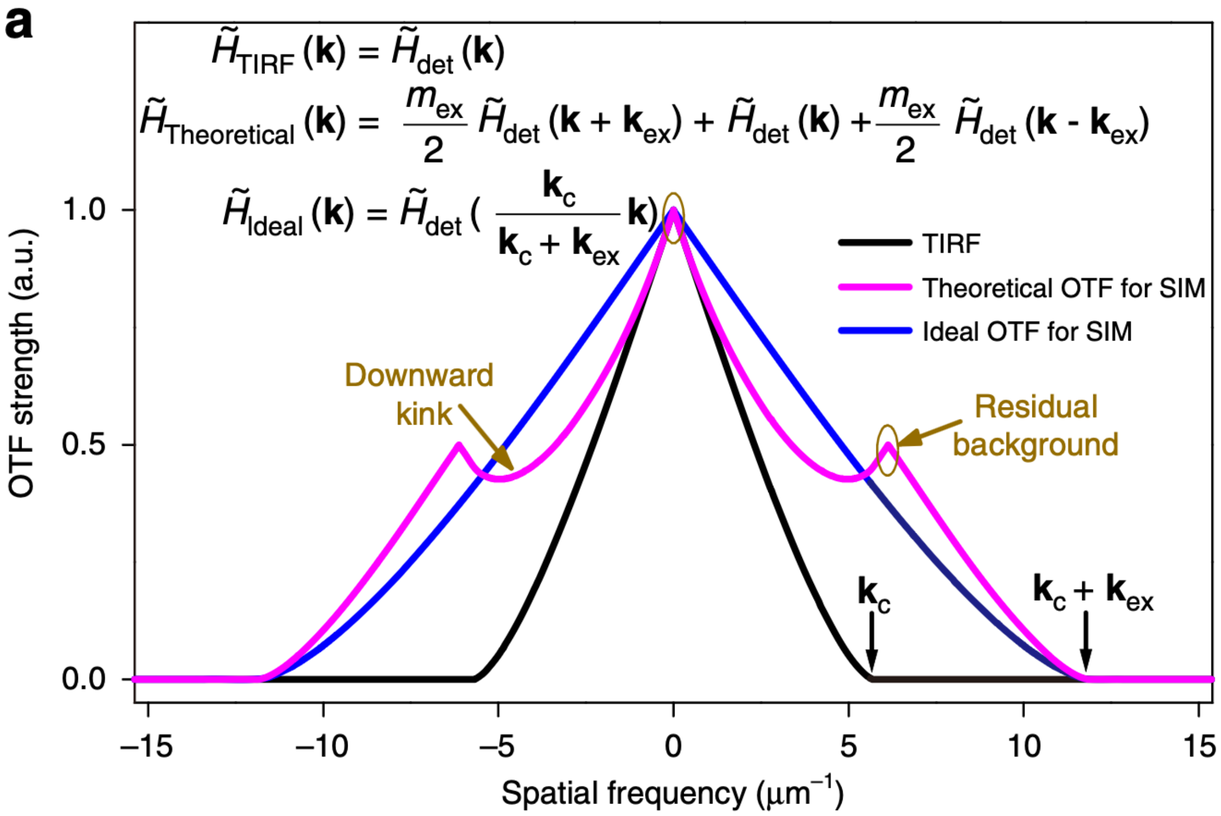


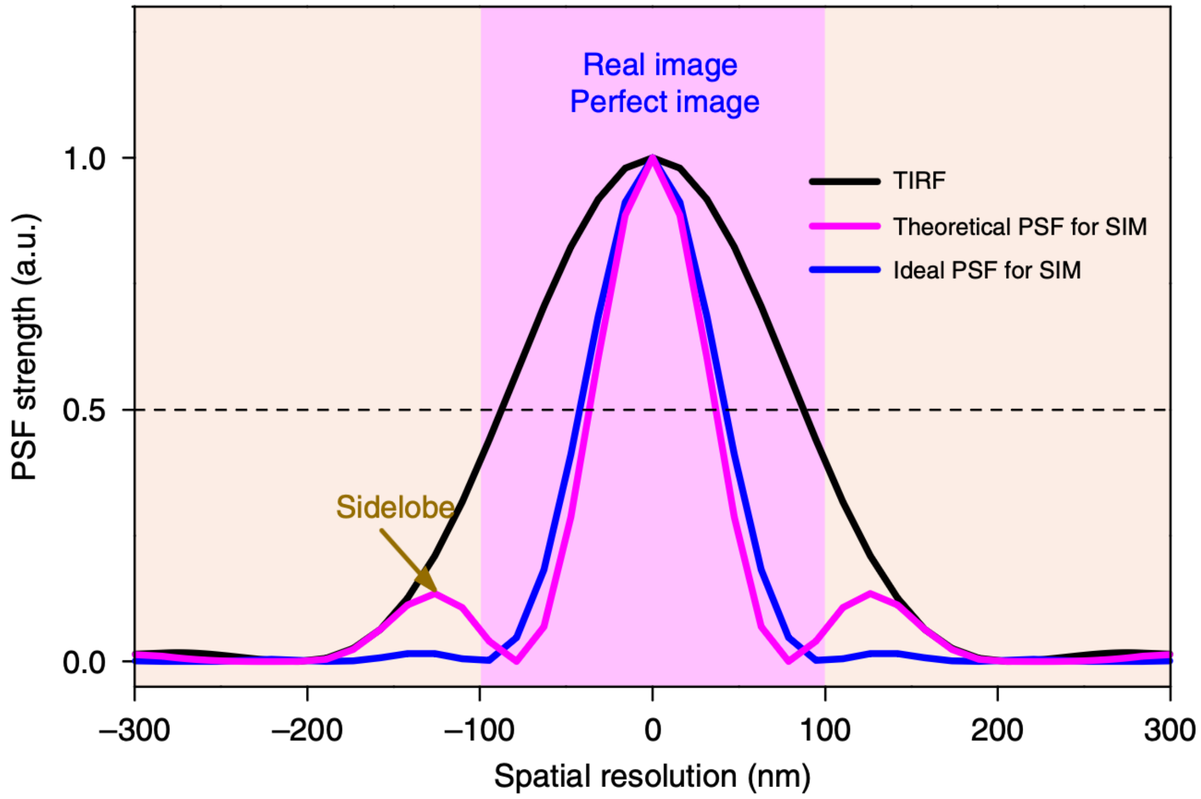
A kind of MMSE filter!

Reference: https://www.youtube.com/watch?v=Nm0UXL1OpRE

Sidelobe Artifacts

Smaller modulation factors will cause the high-order shifted components in the recombined spectrum to be over-amplified. The equivalent OTF of the Wiener-SIM protocol exhibits residual peaks and downward kinks at the middle frequency, which is in essence different from the ideal OTF with doubled resolution.





Reference: https://www.nature.com/articles/s41377-021-00513-w#Sec15

HiFi SIM

The difference between the HiFi- and Wiener-SIM is mainly in the preprocessing procedure (iterations set to 5) and final two-step optimization $\tilde{W}_1(\mathbf{k})$ *and* $\tilde{W}_2(\mathbf{k})$. It can achieve ~2-fold of the diffraction limit

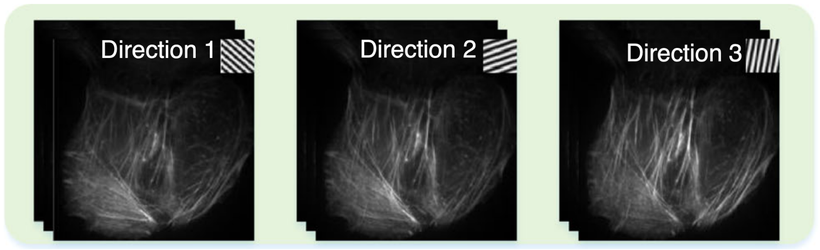
Input Images * 9
(3 Frequency bands)

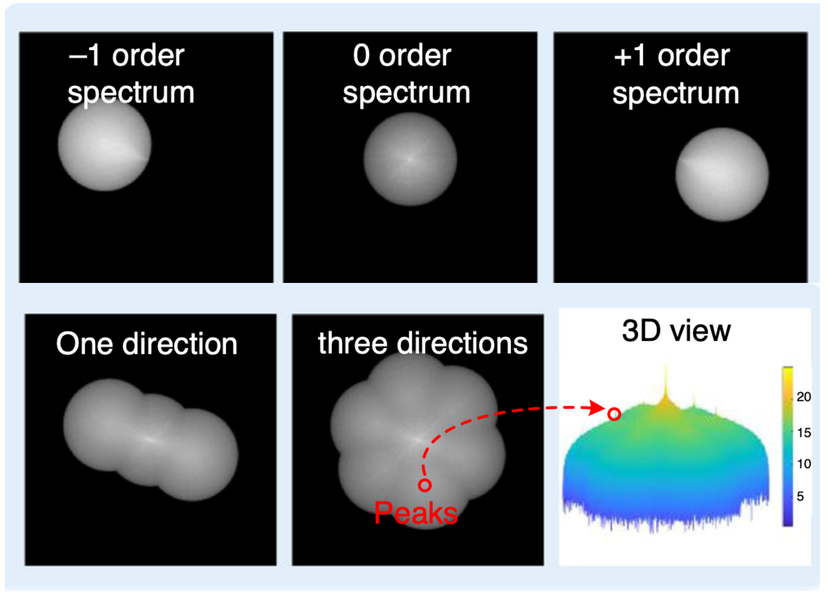
→

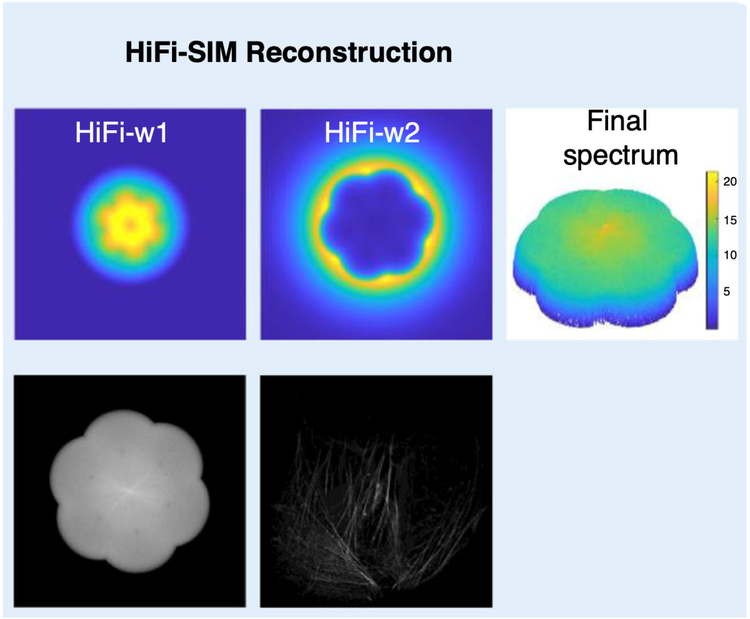
Spectrum Separation,
Translation, & Summation

→

Filtered and
Inverse Fourier Transform







Reference: https://www.nature.com/articles/s41377-023-01204-4

Preprocessing - Richardson–Lucy (RL) deconvolution

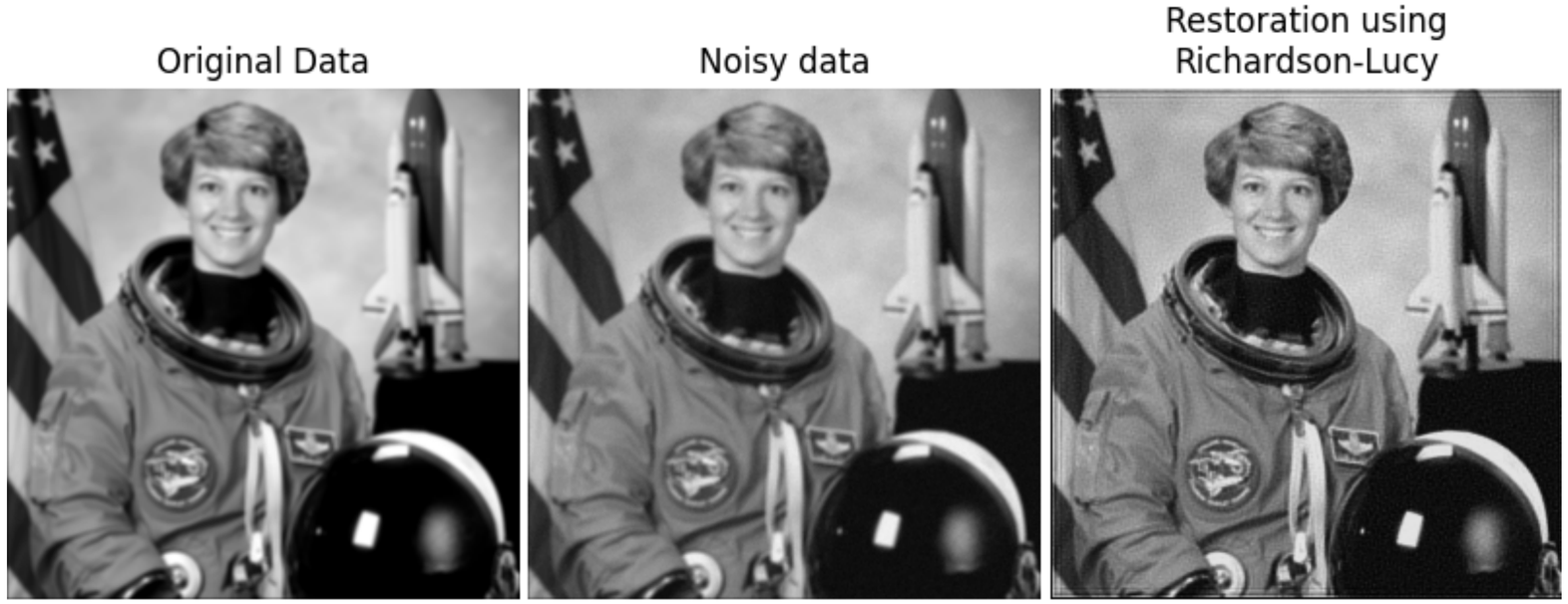
An iterative procedure for recovering an underlying image that has been blurred by a known PSF

- $\hat{I}^{(t+1)} = \hat{I}^{(t)} \cdot \left(\frac{B}{\hat{I}^{(t)} \otimes K} \otimes K^*\right)$

Take Iteration…

Increase the intensity of the high-frequency component

- Reduce the out-of-focus signal-related artifacts
- Enhancing detection of reconstruction parameters.



$\hat{I}$: *Latent Image Estimation*

B : *Blurred Image*

K : *Point Spread Function*

K^* : *Flip PSF*

$\otimes$: *2D Convolution*

Reference: https://www.youtube.com/watch?v=v1kE3mbexko

Reference: https://scikit-image.org/docs/0.23.x/auto_examples/filters/plot_deconvolution.html

Two-Step Optimization: $\tilde{W}_1(\mathbf{k})$, $\tilde{W}_2(\mathbf{k})$

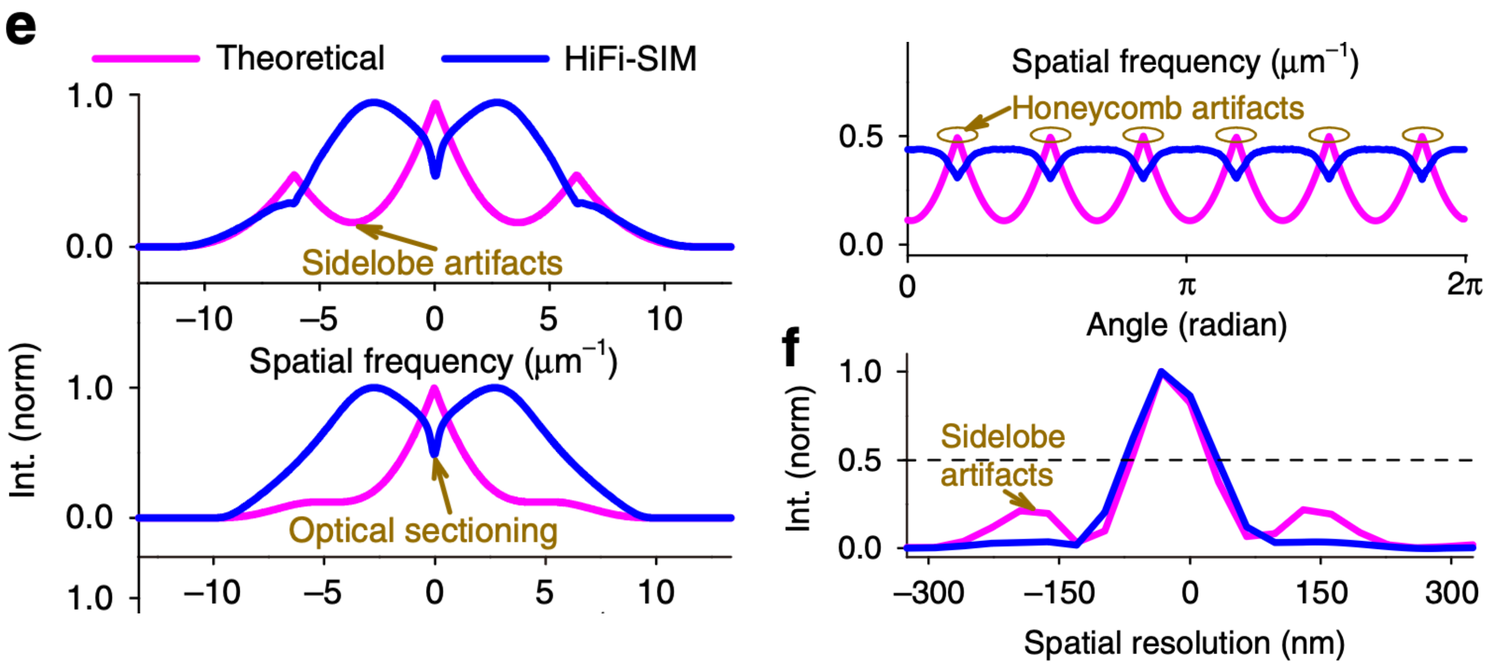
The difference between the HiFi- and Wiener-SIM is mainly in the preprocessing procedure (iterations set to 5) and final two-step optimization $\tilde{W}_1(\mathbf{k})$ *and* $\tilde{W}_2(\mathbf{k})$

$\tilde{W}_1(\mathbf{k})$:

> to correct $\tilde{H}_{Thoretical}(\mathbf{k})$ to be close to $\tilde{H}_{Ideal}(\mathbf{k})$

$\tilde{W}_2(\mathbf{k})$:

> to recover the high-frequency signals suppressed by the optimized OTF



However, both preprocessing and optimization are of huge computational complexity!!!

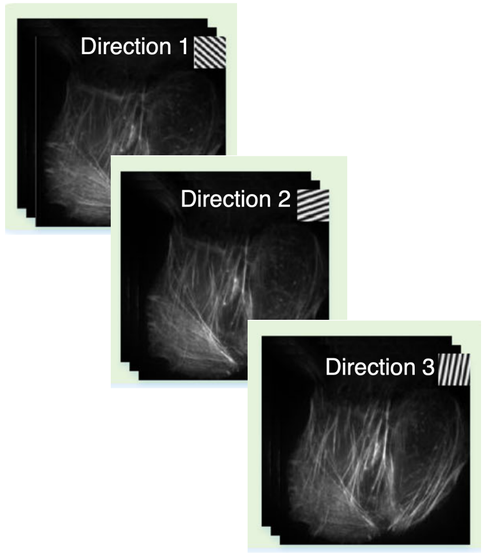
Reference: https://www.nature.com/articles/s41377-021-00513-w#Sec15

JSFR SIM

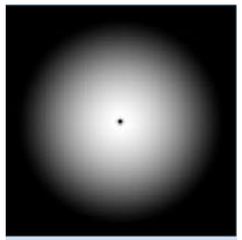
It is a spatial domain-based SIM reconstruction instead of a Fourier domain-based method. The reconstruction time is 10.2 ms for 512*512raw images

Parameters Estimation

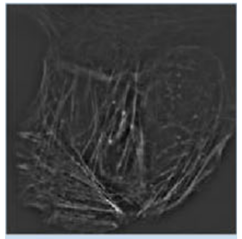
Input Images * 9
(3 Frequency bands)



Filtering

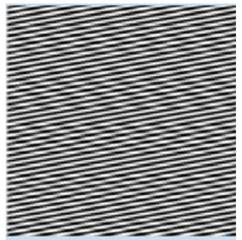


Notchfilter



Filtered raw images

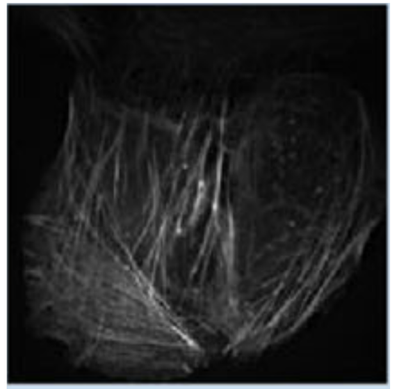
Calculating coefficient matrix & multiplying filtered raw images



Coefficient matrix

Intermediate images

Summing (1-9) & Wiener Filtering



Super-resolution image

Reference: https://www.nature.com/articles/s41377-023-01204-4

JSFR AR SIM

- HiFi- and JSFR-SIM both employed the OTF compensation and attenuation to enhance the spatial resolution and suppress the background fluorescence.

=> This is equivalent to applying a bandpass filter $a(\mathbf{k})\tilde{H}^*(\mathbf{k})$ on all the preprocessed raw images
=> The extra spectrum information gained by RL deconvolution will be suppressed by the bandpass filter
=> RL deconvolution doesn't provide extra spectrum information of the sample than Wiener-type filter

Replace the RL deconvolution with Wiener-type filter to accelerate!

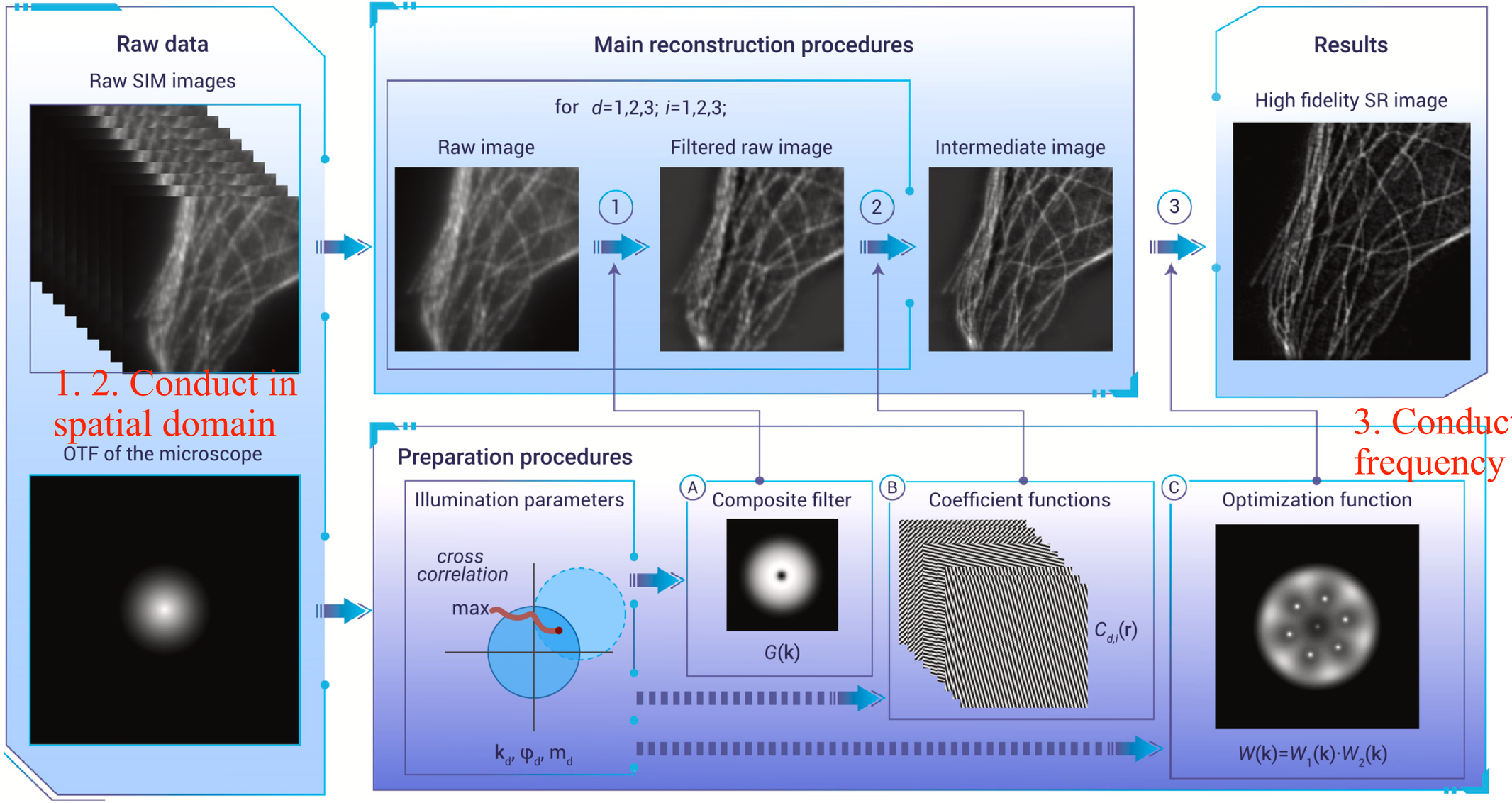
$\tilde{H}(\mathbf{k})$: OTF of the microscope

- Combine the two optimization steps in HiFi-Sim into a single one, since the two optimization functions $\tilde{W}_1(\mathbf{k})$ *and* $\tilde{W}_2(\mathbf{k})$ in HiFi-SIM do not vary with the sample distribution.

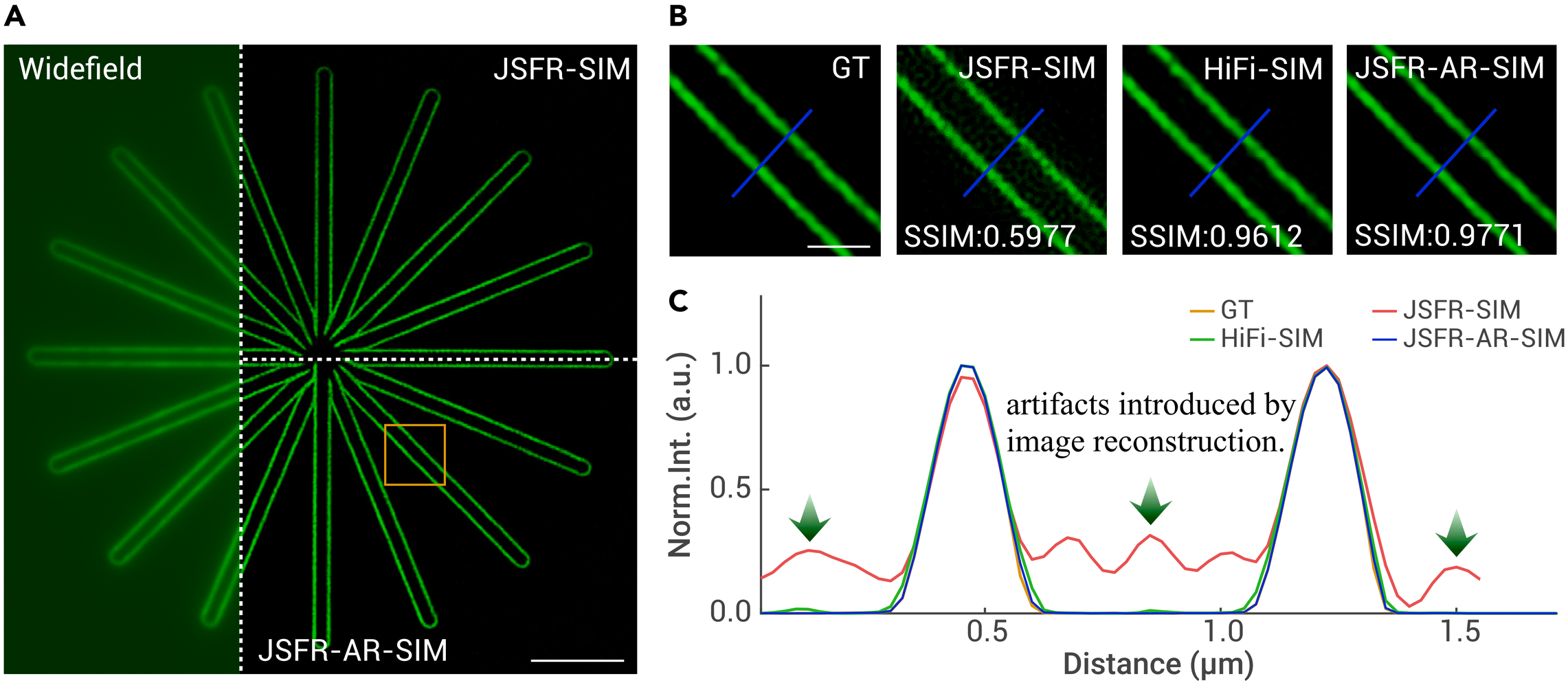
$$\tilde{W}(\mathbf{k}) = \tilde{W}_1(\mathbf{k}) \cdot \tilde{W}_2(\mathbf{k})$$

- The parameters of the illumination field (wave vectors, initial phases, and modulation depth) are pre-computed for later use, along with coefficient functions $c_{d,i}(\mathbf{r})$, composite filter $\tilde{G}(\mathbf{k})$, and the combined optimization function $\tilde{W}(\mathbf{k})$.

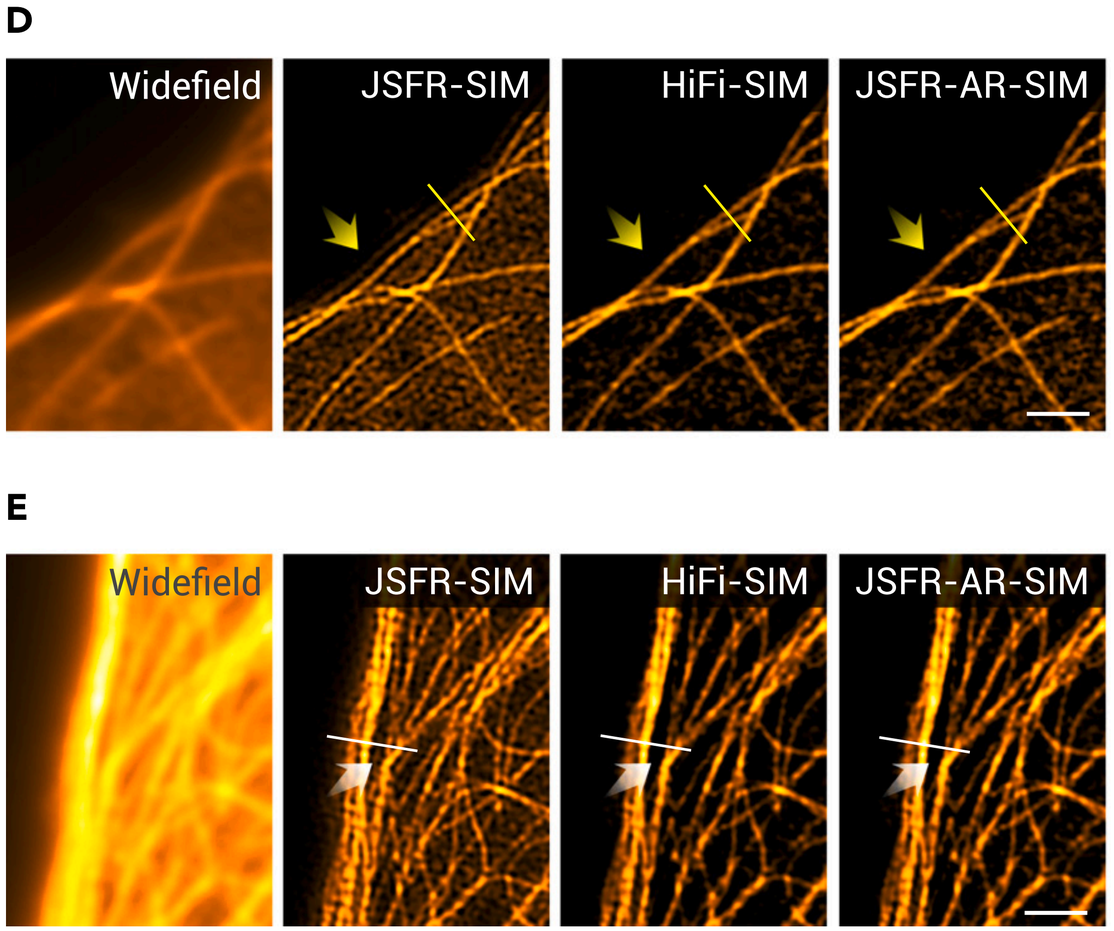
JSFR AR SIM

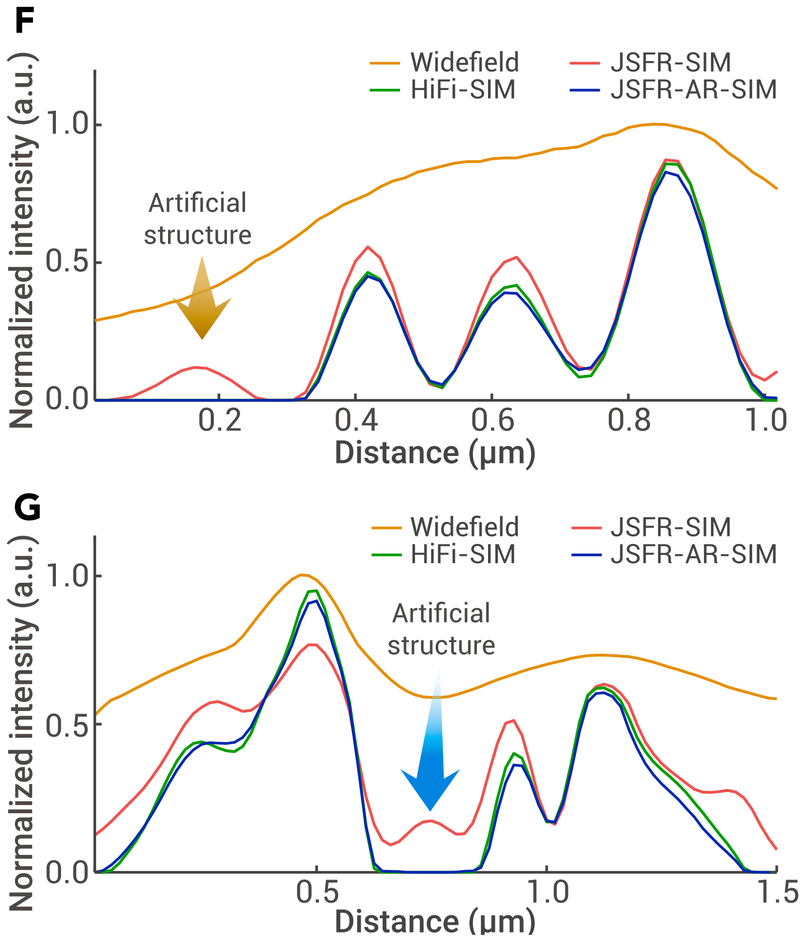

Raw data
Raw SIM images
1. 2. Conduct in spatial domain
OTF of the microscope
Main reconstruction procedures
for d=1,2,3; i=1,2,3;
Raw image
Filtered raw image
Intermediate image
1
2
3
Results
High fidelity SR image
3. Conduct in frequency domain
Preparation procedures
Illumination parameters
cross correlation
max
k_d, φ_d, m_d
A
Composite filter
G(k)
B
Coefficient functions
C_d,i(r)
C
Optimization function
W(k)=W_1(k)·W_2(k)

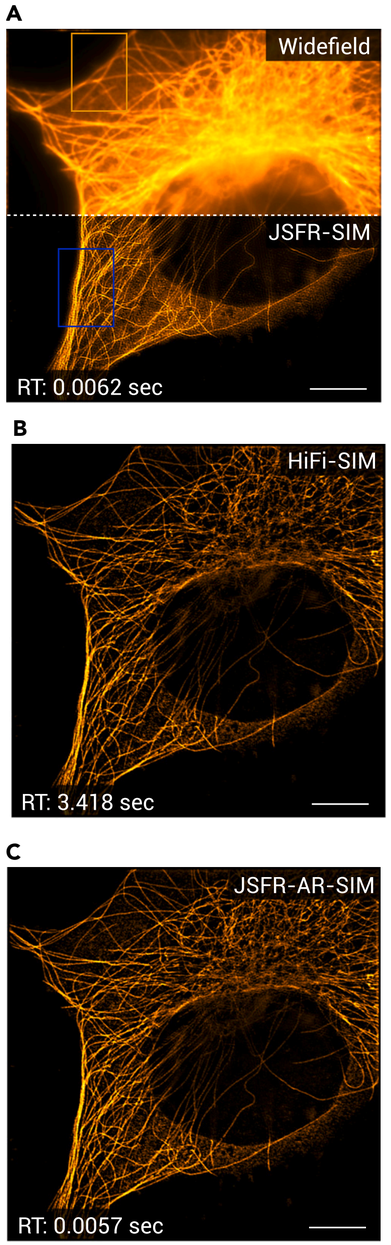
Quality Results - Argo-SIM



Quality Results - Microtubules







Speed Results - Computation Time

Input image size	Output image size	Acquisition time (ms)[a]	Execution time of JSFR-AR-SIM (ms)		Execution time of HiFi-SIM (ms)	
			CPU[b]	GPU[c]	CPU	GPU
2,048 × 2,048	4,096 × 4,096	95.0	5,940.1 ± 776.1 (9.9)[d]	88.7 ± 12.3 (13.7)	58,806.2 ± 1,290.8	1,205.6 ± 13.5
1,024 × 1,024	2,048 × 2,048	45.0	1,340.9 ± 70.8 (10.2)[d]	21.5 ± 6.1 (16.4)	13,720.8 ± 616.0	352.2 ± 6.3
512 × 512	1,024 × 1,024	22.5	274.9 ± 7.3 (12.4)	5.7 ± 4.5 (17.3)	3,412.6 ± 186.6	98.5 ± 3.7
256 × 256	512 × 512	11.3	68.1 ± 1.7 (12.7)	3.1 ± 0.1 (10.0)	866.2 ± 14.3	31.1 ± 0.6

JSFR-AR-SIM reconstructs SR images 2- to 4-fold more rapidly than it takes to acquire them

1. Platform: MATLAB
2. Personal computer (i7-9700K@3.6GHz, NVIDIA GeForce RTX 3080ti 12GB, Samsung 860 EVO 500GB SSD)

Results & Analysis - Workflow

HiFi-SIM

2.13s
Calculate attenuated OTF & Weight Functions

10.37s (~78%)
R-L deconvolution for each raw image

1.51s
Separate components in each pattern orientation

0.54s
Multiply each component with attenuated OTF

0.86s
Shifts and combines all the components

0.01s
Multiply the spectrum with the weight function

Inverse Fourier Transform

HiFi-SIM: 292*FT + 241*PM + 30*PA + 6*PP

JSFR-AR-SIM

Estimation the illumination parameters

Calculate Coefficient Functions, Composite Filter, Weight Functions

Preprocessing: background subtraction, upsampling, etc.

1.04s
Filter all raw images with composite filter

0.19s
Multiply with coefficient functions and sum all the product

0.05s
Transform to frequency domain and multiply with weight functions

Inverse Fourier Transform

JSFR-AR-SIM: 20*FT + 19*PM + 8*PA

FT: (Inverse Fourier Transform) PM: Pointwise Multiplication

PA: Pointwise Addition PP: Pointwise Power

Reference: https://www.cell.com/cms/10.1016/j.xinn.2023.100425/attachment/2ea5b0e0-1a28-4360-8b50-26c2ee0fb6e6/mmc1.pdf

Merits & Future Possibility

- High Speed + High-fidelity in a single framework.

  => achieve real-time reconstruction with no sidelobe artifacts

- Simplified imaging workflow for a single SR mode without the need to disjointly change between wide-field mode and SR mode as in HiFi-SIM

- Be suitable to combine with better parameter estimation algorithms to improve the accuracy of reconstructed images (e.g. PCA, Deep Learning)

- It's anticipated to even increase the overall speed by reducing the number of frames required to produce an SR image from nine to four

References

[1] Rapid, artifact-reduced, image reconstruction for super-resolution structured illumination microscopy
https://www.the-innovation.org/article/doi/10.1016/j.xinn.2023.100425

[2] A Sibelobe Suppressing Beamformer for Coherent Plane Wave Compounding
https://www.mdpi.com/2076-3417/6/11/359

[3] Argo-SIM
https://www.klv.co.jp/product/slide-microscope/argo-hm-v2.html

[4] Superresolution structured illumination microscopy reconstruction algorithms: a review
https://www.nature.com/articles/s41377-023-01204-4

[5] Wiener Filter
https://www.youtube.com/watch?v=Nm0UXL1OpRE

[6] High-fidelity structured illumination microscopy by point-spread-function engineering
https://www.nature.com/articles/s41377-021-00513-w#Sec15

[7] Blind Deconvolution with Richardson Lucy Algorithm
https://www.youtube.com/watch?v=v1kE3mbexko

[8] Scikit-image: image deconvolution
https://scikit-image.org/docs/0.23.x/auto_examples/filters/plot_deconvolution.html